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Dark Energy: Mystery & Investigation

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Postdoctoral Lunch Talk, Argonne, IL, Oct. 1, 2008

Outline

- Introduction to cosmology



DARK ENERGY
SURVEY

- Dark Energy Survey

- Dark Energy Survey Supernovae



- Simulating & fitting supernova light curves

- Summary & conclusions

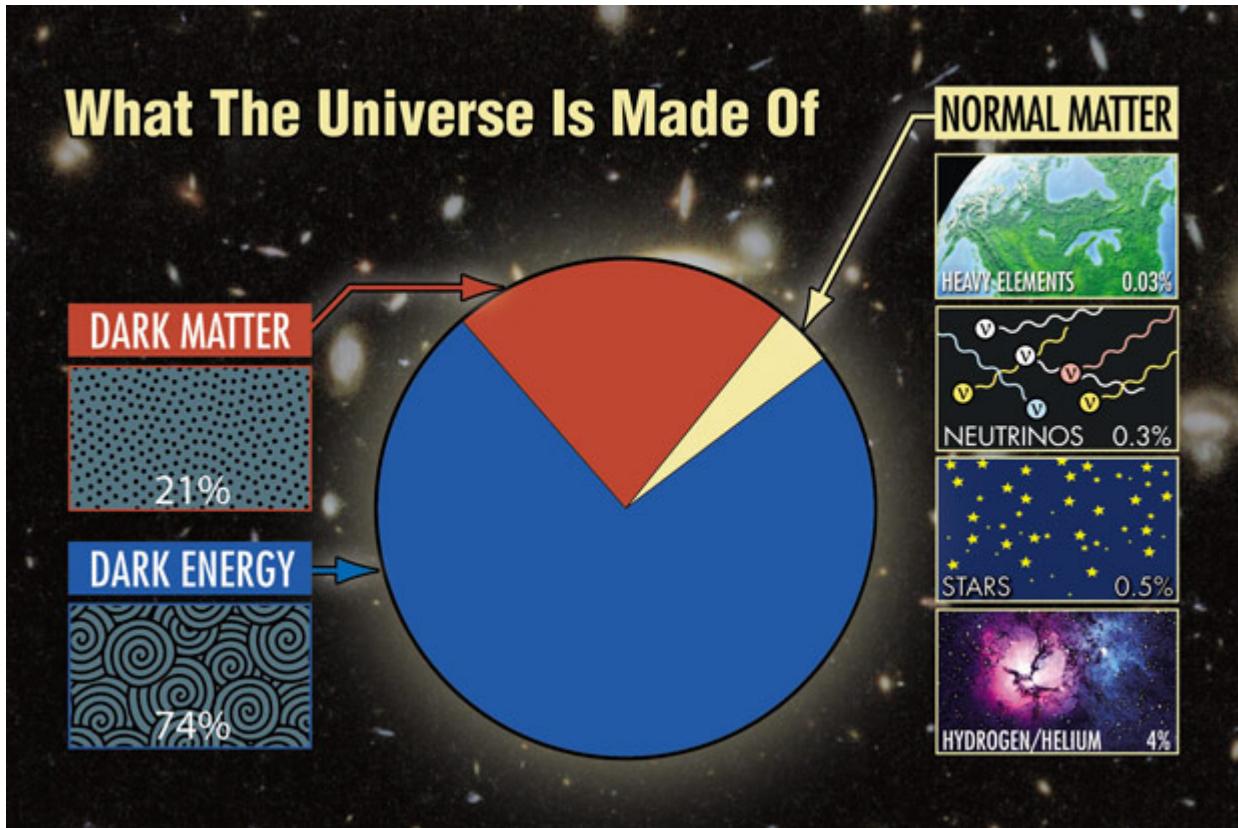


University of Chicago

Fundamental Motivation

Discovering the evolution & ultimate fate
of the Universe and determining what
constitutes 95% of the Universe!

Have A Slice Of Universe Pie



Courtesy: <http://hetdex.org>

Dark Energy Requires Fundamental Particle Physics Change



- Motivated U.S. Dept. of Energy to invest in astrophysics
 - more than \$500M over next decade
 - compare that to ~\$1M/year allocated in previous years
- Is it Einstein's vacuum energy?
 - aka, the Cosmological Constant (Λ)
 - best estimate of current theory is off by factor of 10^{120}
- New fundamental, zero-spin, heavy scalar particle?
 - nothing like it ever seen before but is discovery eminent?
 - Higgs boson: hypothetical but predicted by Standard Model
 - would give mechanism by which particles acquire mass
 - if exists, Large Hadron Collider accelerator should find it
- Modified Theory of Gravity?
 - hypothesis that Einsteinian gravity breaks down at large scales
 - conflicts with current observations

Big Problem For Modified Gravity (MG): The Bullet Cluster

Best evidence to date for existence of dark matter:
gas (pink) and gravitational mass distribution
(blue) don't match – very hard to explain with MG

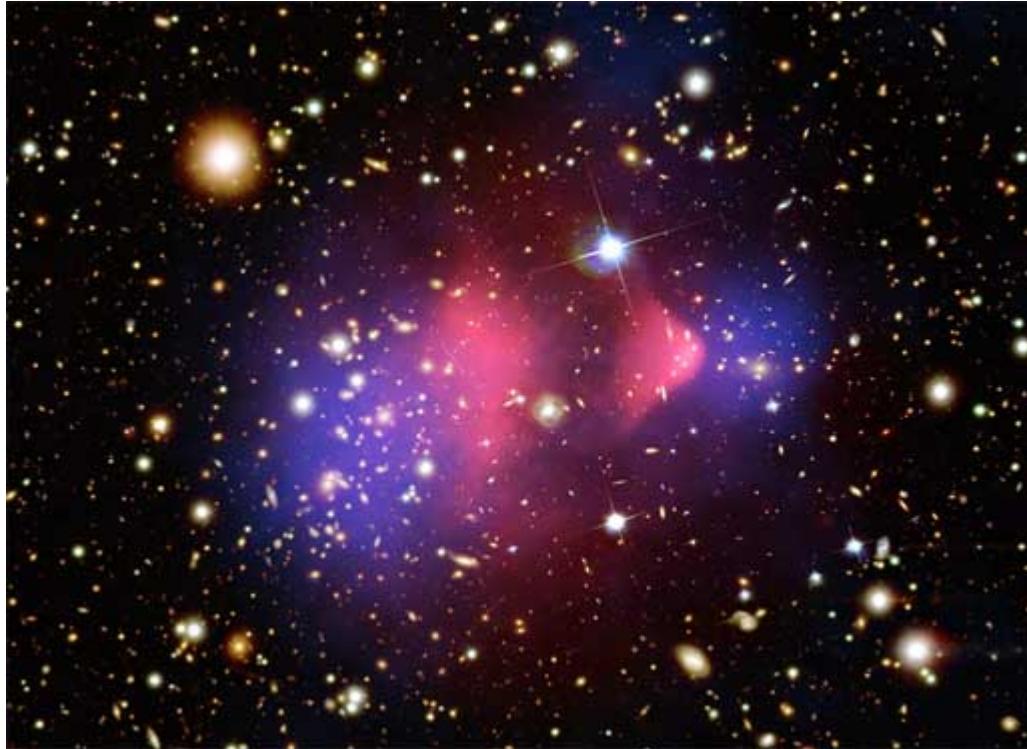


Image credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

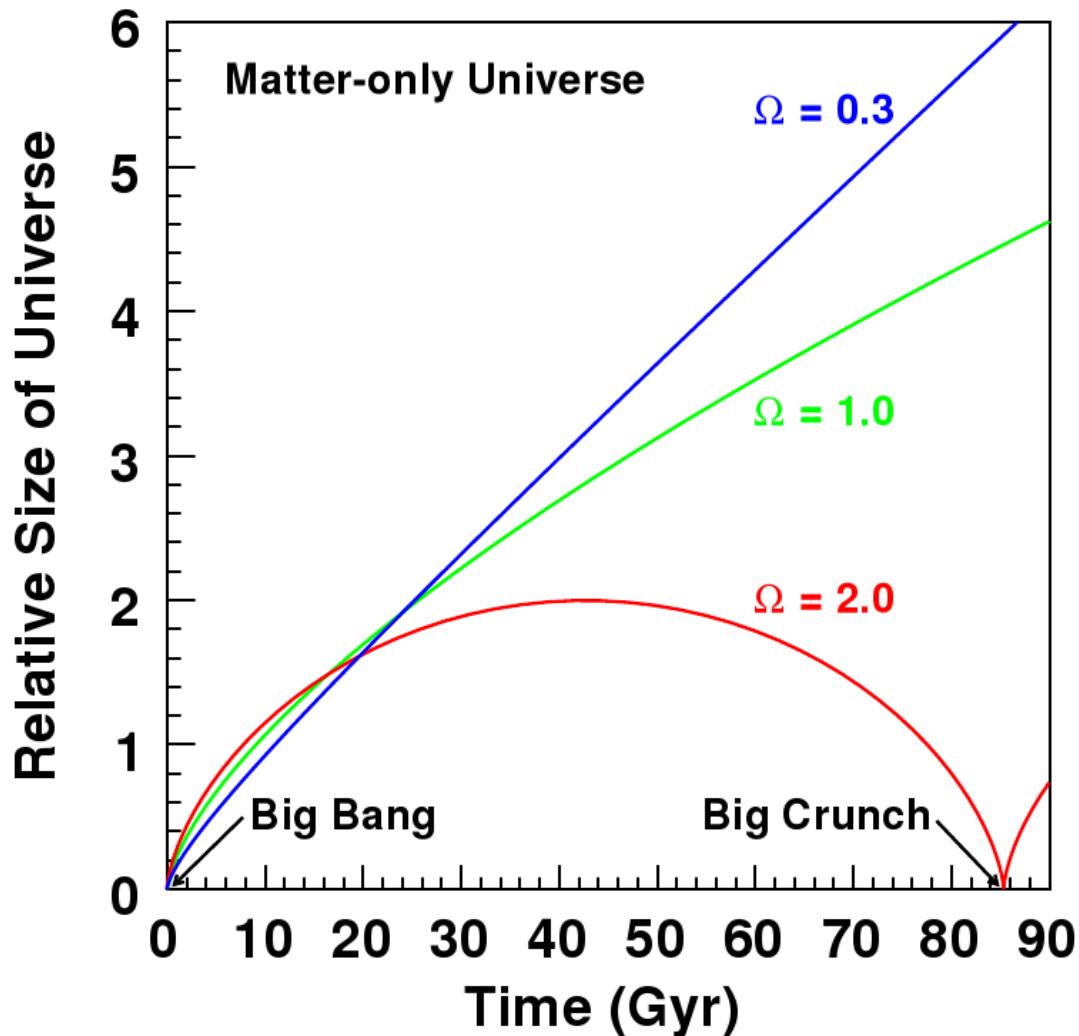
Quantifying Past & Future Evolution

Observation:
Universe is expanding!

Evolution depends on
energy density ρ

Define: $\Omega \equiv \rho/\rho_{\text{crit}}$

ρ_{crit} : matter density
required to eventually
halt the expansion of
the Universe



Quantifying Cosmology

Theory motivates & data show that Universe has:

$$\Omega_{\text{tot}} = 1$$

Observations indicate matter comprises only 25%:

$$\Omega_m = 0.25$$

What makes up the other 75%?

Towards An Answer: Type Ia Supernovae

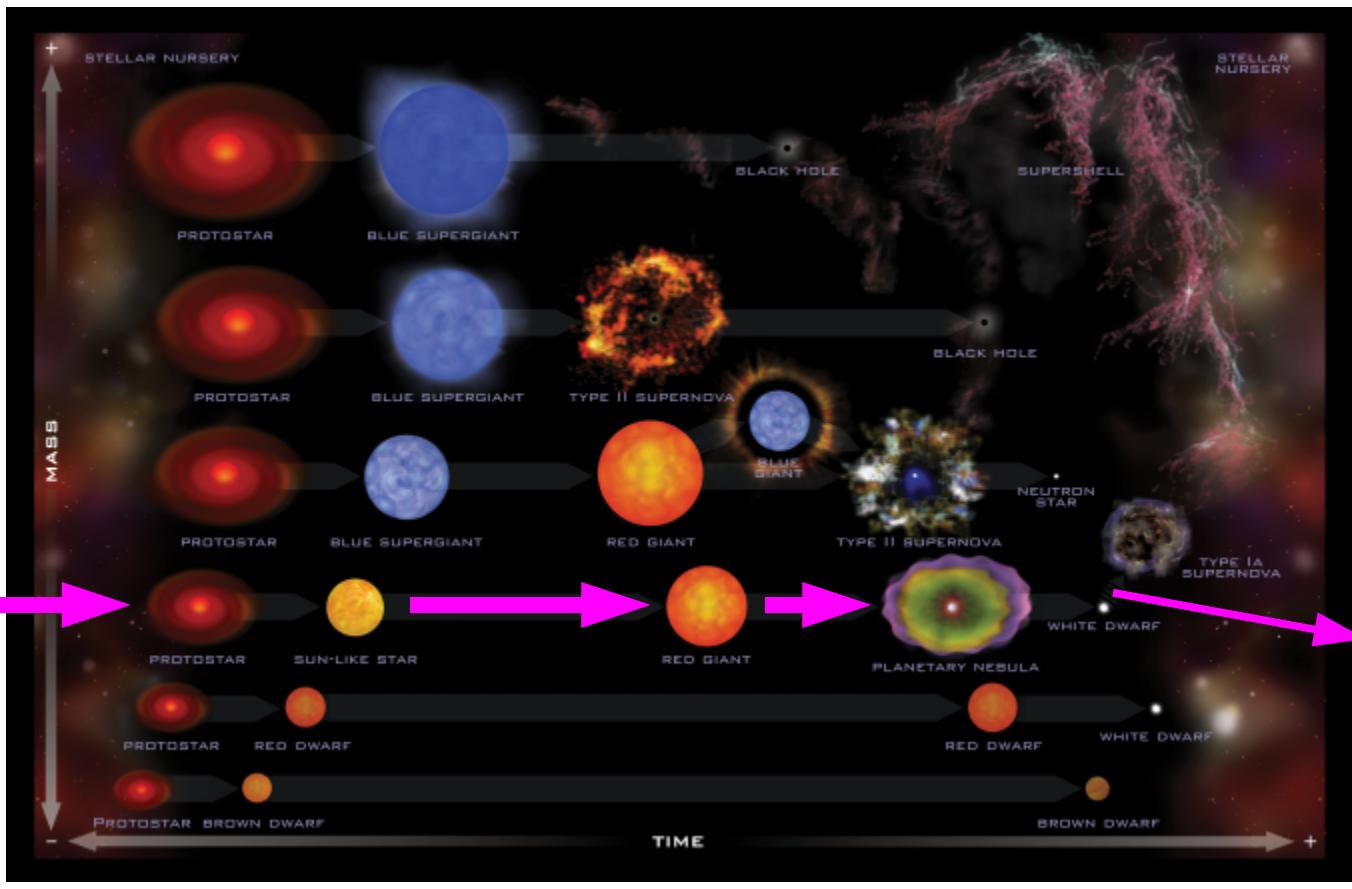
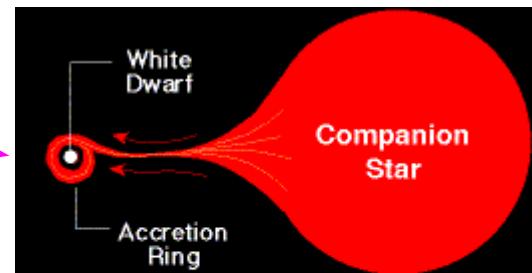
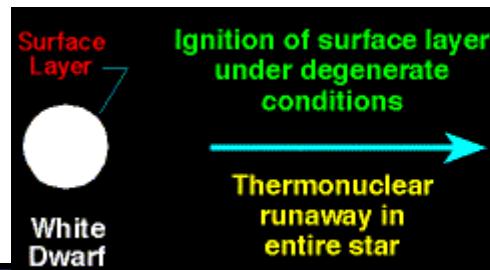


Image courtesy <http://www.siprep.org/faculty/aokeefe>

Figure courtesy
<http://csep10.phys.utk.edu/astr162>



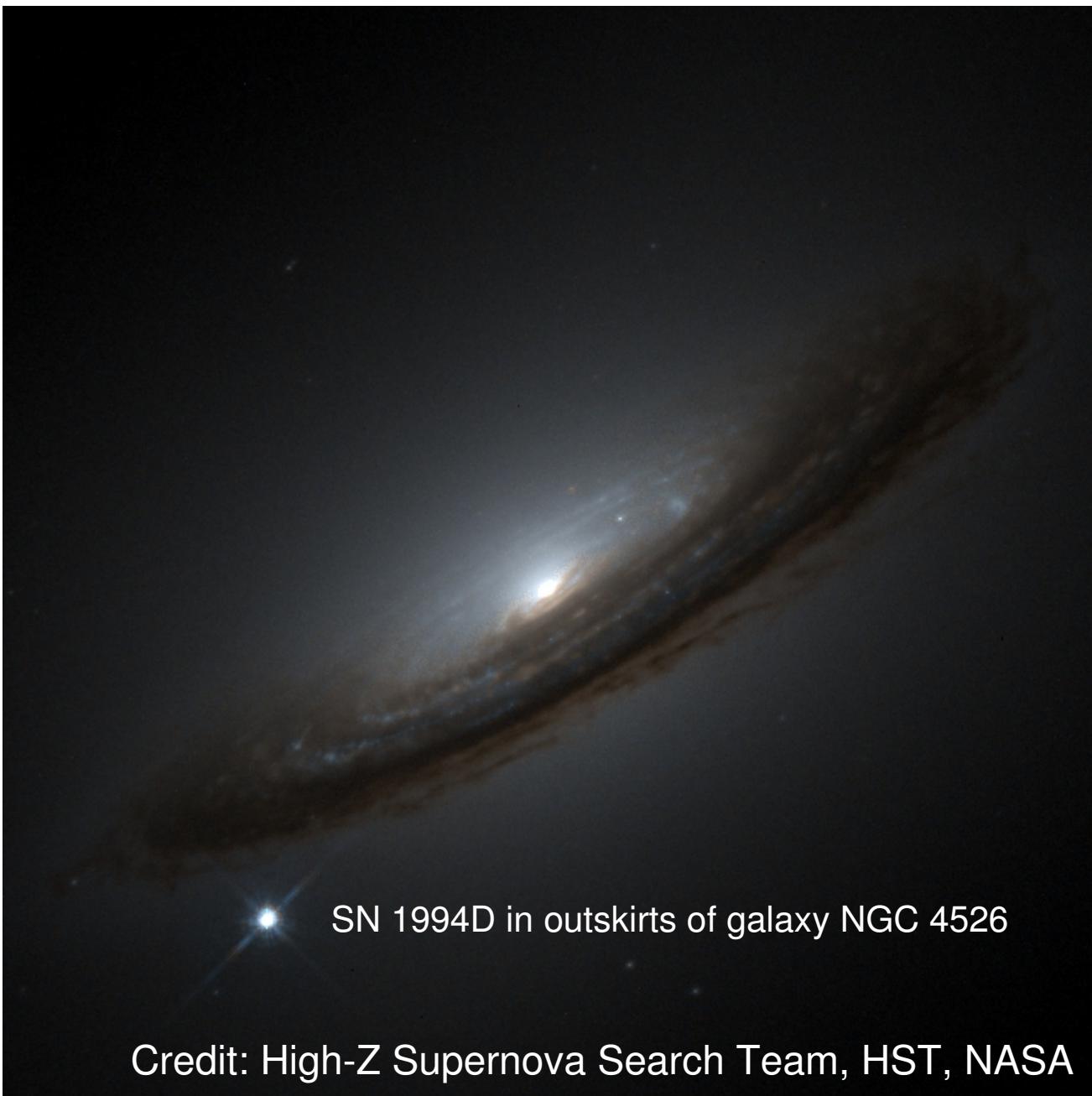
Thin hydrogen surface layer
 accumulated on white dwarf
 through accretion ring



Thermonuclear
 explosion
 consumes
 the entire white
 dwarf star

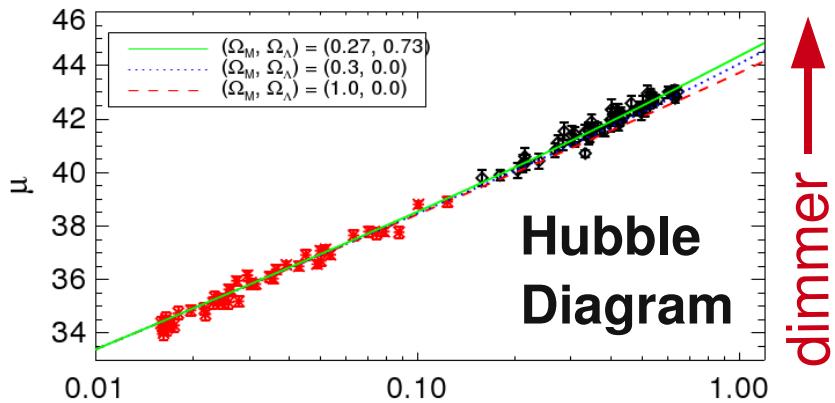
BRIGHT!

NCG 4526 is
~55 million light
years away from
Earth ⇒ the light
from SN 1994D
started traveling
towards Earth
~55 million years
before 1994!

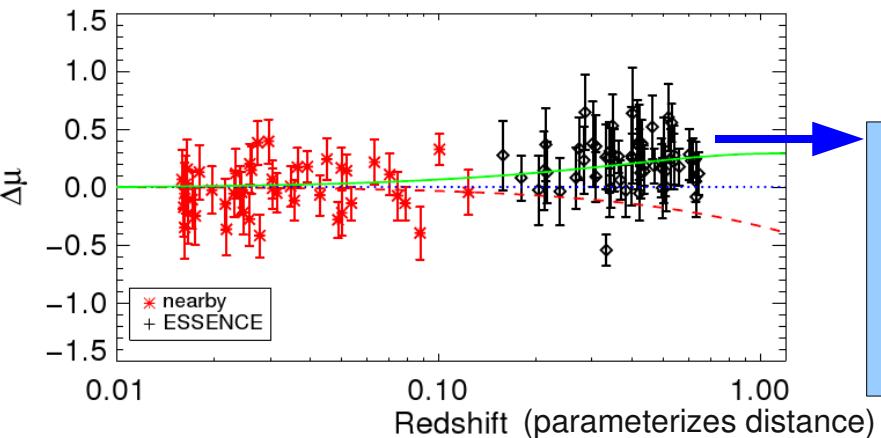




SNe As Standard Candles



Credit: W. M. Wood-Vasey
et al., 2008, ApJ submitted



Distance modulus:

$$\mu = m - M = 5 \log_{10}(d/10 \text{ pc})$$

d = distance (1 pc = 3.09×10^{16} m)

m = apparent magnitude of object

M = absolute magnitude of object

$$m_1 - m_2 = -2.5 \log_{10}[(L_1/L_2)(d_2/d_1)^2]$$

L = luminosity (units: energy/sec)

Distant SNe dimmer than predicted
for a matter-only Universe!
(originally discovered in 1998)

Quantitative Framework For Dark Energy

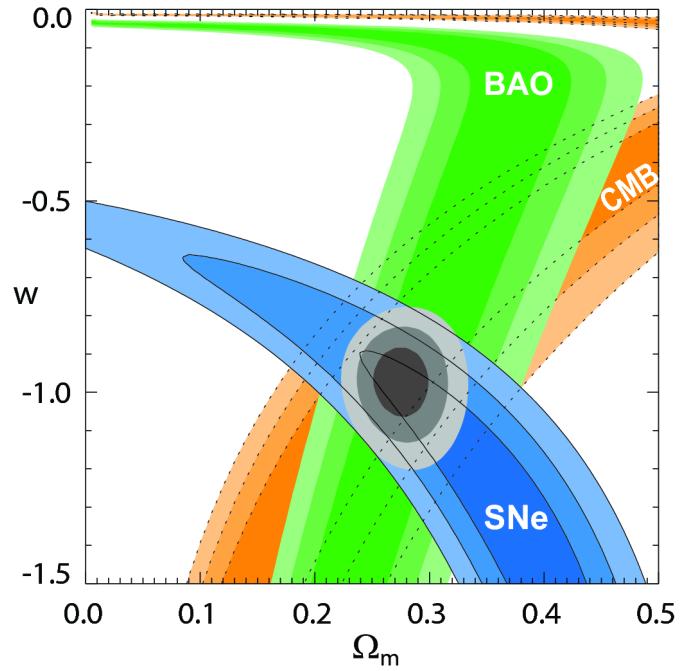
Explanation: expansion of Universe is accelerating due to dark energy that has strongly negative pressure (p_{DE})

Dark energy equation of state: $w = p_{\text{DE}}/\rho_{\text{DE}}$

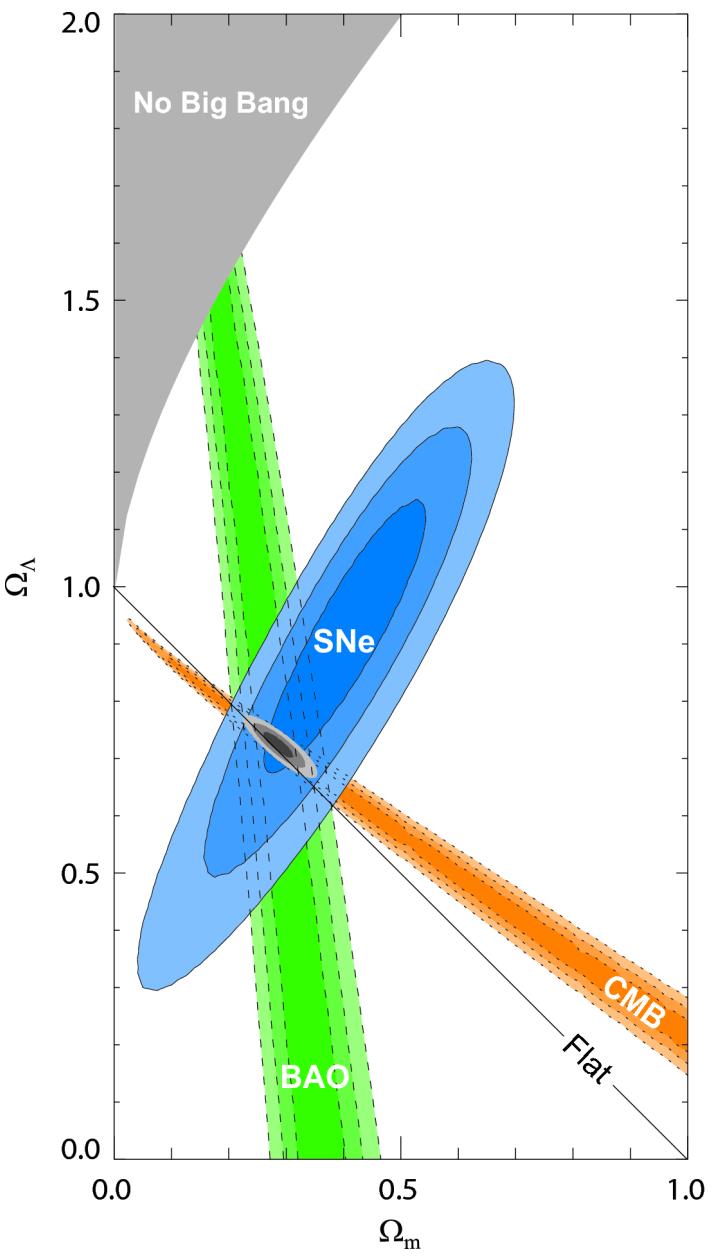
Dark energy density today: $\Omega_{\text{DE}} = \rho_{\text{DE}}/\rho_{\text{crit}}$

Default cosmology: $w = -1$
Einstein's cosmological constant (Λ)

Current Constraints



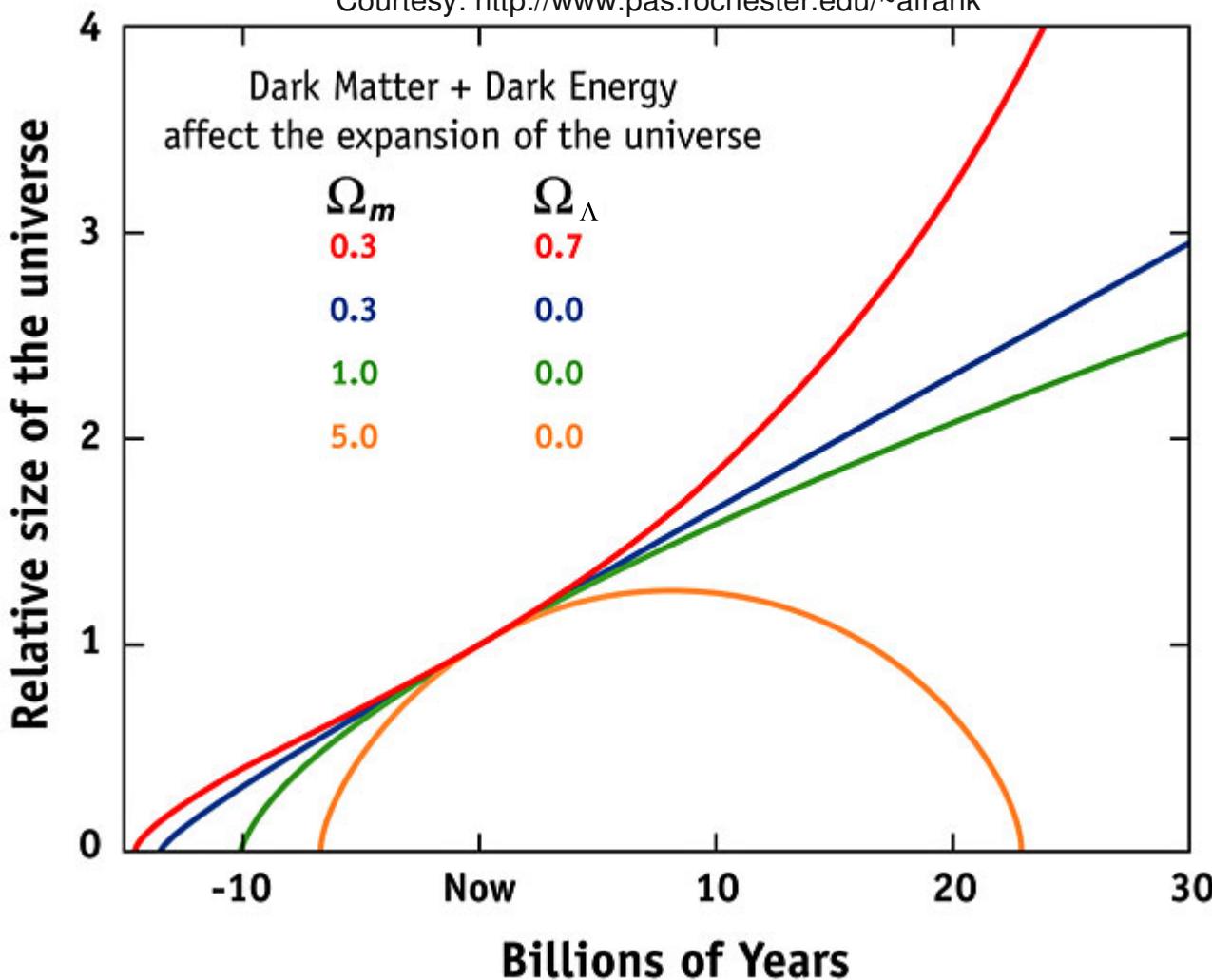
Credit: Kowalski et al. 2008, ApJ, accepted



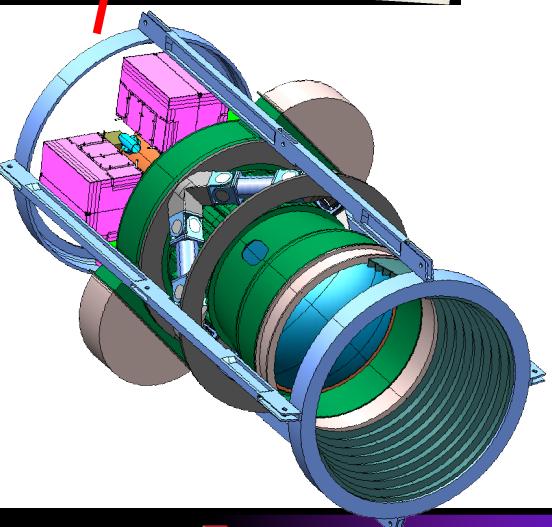
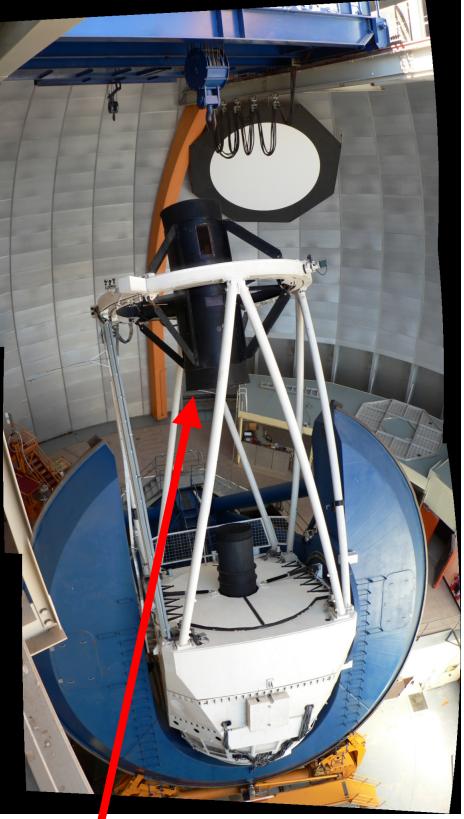
Expansion Revisited

EXPANSION OF THE UNIVERSE

Courtesy: <http://www.pas.rochester.edu/~afrank>



Dark Energy Survey (DES)



DES will survey 5000 square degree of sky and provide new 520Mpixel CCD camera (DECam) for Blanco 4m telescope at CTIO, Chile, in exchange for 525 survey nights over 5 years starting in 2011

DE investigation via 4 independent probes:

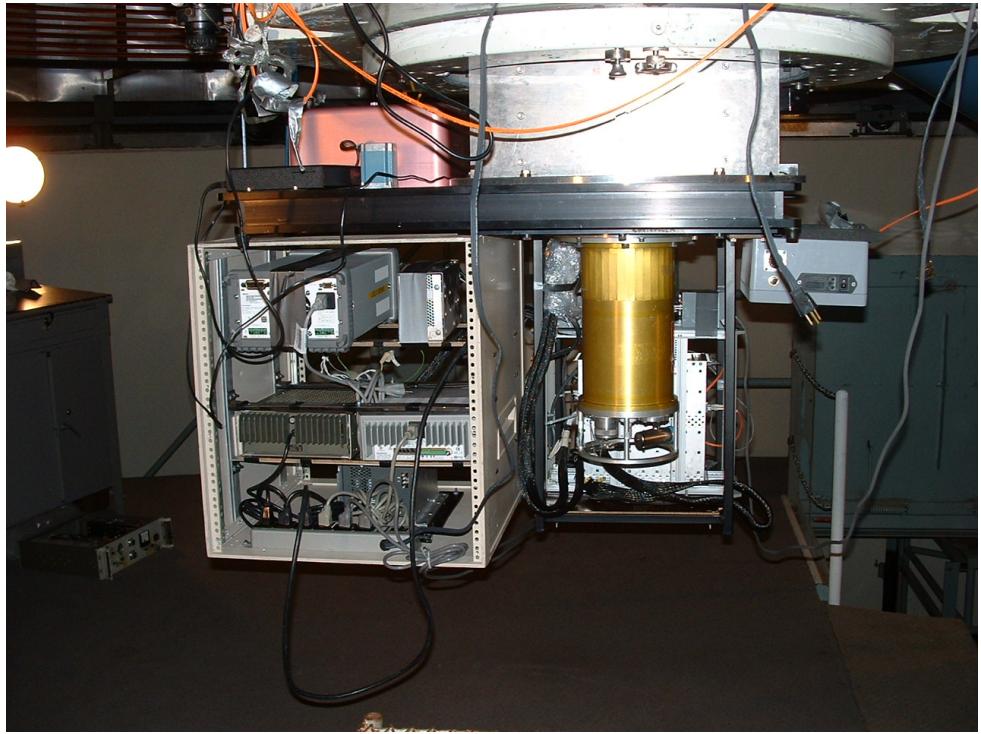
- 1) Galaxy angular clustering
- 2) Weak gravitational lensing tomography
- 3) Baryon acoustic oscillations
- 4) SN Ia distances

DES is expected to observe $\sim 10^6$ galaxies & will obtain redshifts for the South Pole Telescope survey

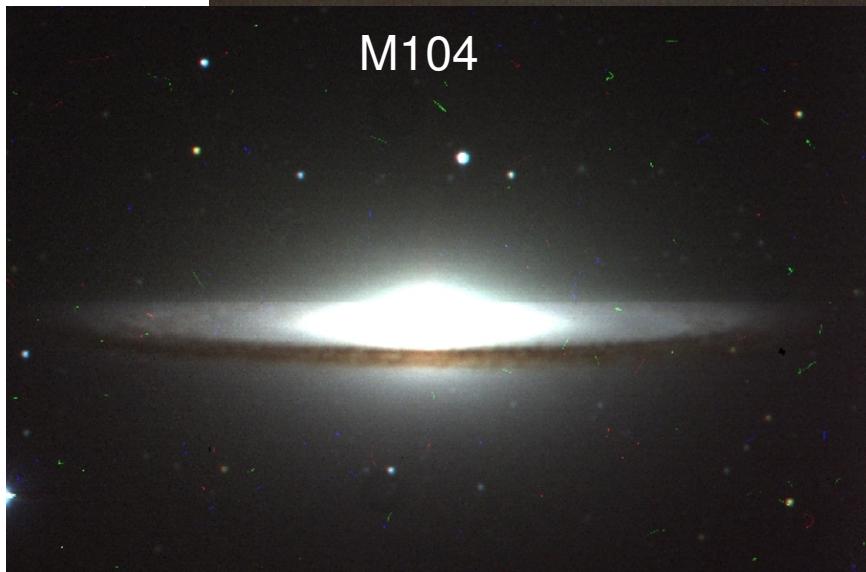
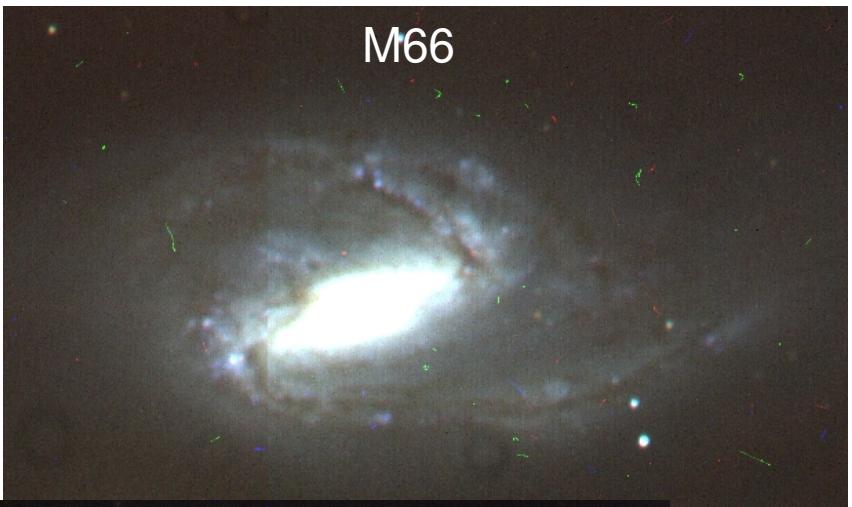


Test DES

Recent test on 1m telescope at CTIO (1 week test with 1 CCD)



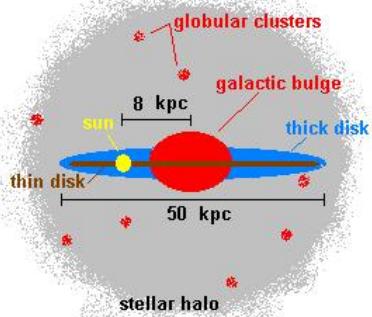
DES Test Images



**100-sec raw images
taken with single
2Kx2K DES CCD on
1m telescope**

The Blanco & The Milky Way

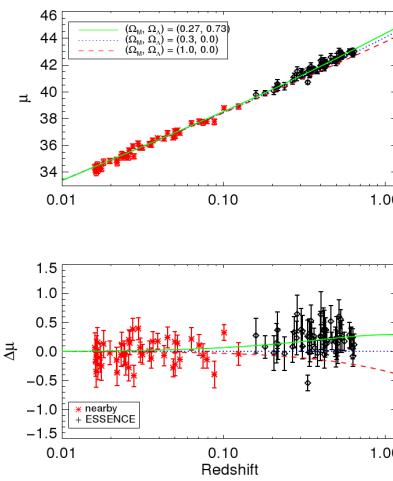
Image courtesy
Mike Fanelli



The Blanco telescope dome at Cerro Tololo, Chile. Single, non-composite image taken using a 2Kx2K scientific CCD temporarily mated to a custom camera. 20 sec exposure, 40mm f/4 lens, starlight only.
Credit: Roger Smith/NOAO/AURA/NSF

DES Supernovae

- DES time allocation fixes total supernovae (SNe) exposure time
 - 1000 hr planned over 5-year survey period
 - maximal use of non-photometric time (~500 hr) planned
 - Time per field & number of fields can be simulation optimized
 - ultra-deep strategy (3 square degrees = 1 DES field)
 - deep strategy (9 square deg.)*
 - shallow but wide strategy (27 square deg.)
 - hybrid strategy, e.g., 3 deep + 2 wide (15 square deg.)
 - Need redshift for each SN to make Hubble Diagram →
- * Highlighted in DES DOE proposal



DES Redshifts And Spectroscopy

- Using SNe Ia for cosmology
 - need *redshift* of each SN
 - requires spectrum or detailed colors
 - \Rightarrow formulate spectroscopic strategy

- Spectroscopy of full SNe sample?
 - redshift error ~ 0.01
 - expensive (spectroscopic telescope follow-up time)

- Redshift critical for distinguishing type Ia & II SNe
 - spectroscopic follow-up for $\sim 25\%$ of SN sample
 - rest: photometric redshifts in real time (error $\sim 0.02\text{-}0.03$) & host galaxy follow-up (errors 0.001)

$$1+z \equiv \lambda_{\text{obs}}/\lambda_{\text{emit}}$$

$$z \equiv \text{redshift}$$

λ_{obs} = observed wavelength

λ_{emit} = emitted wavelength

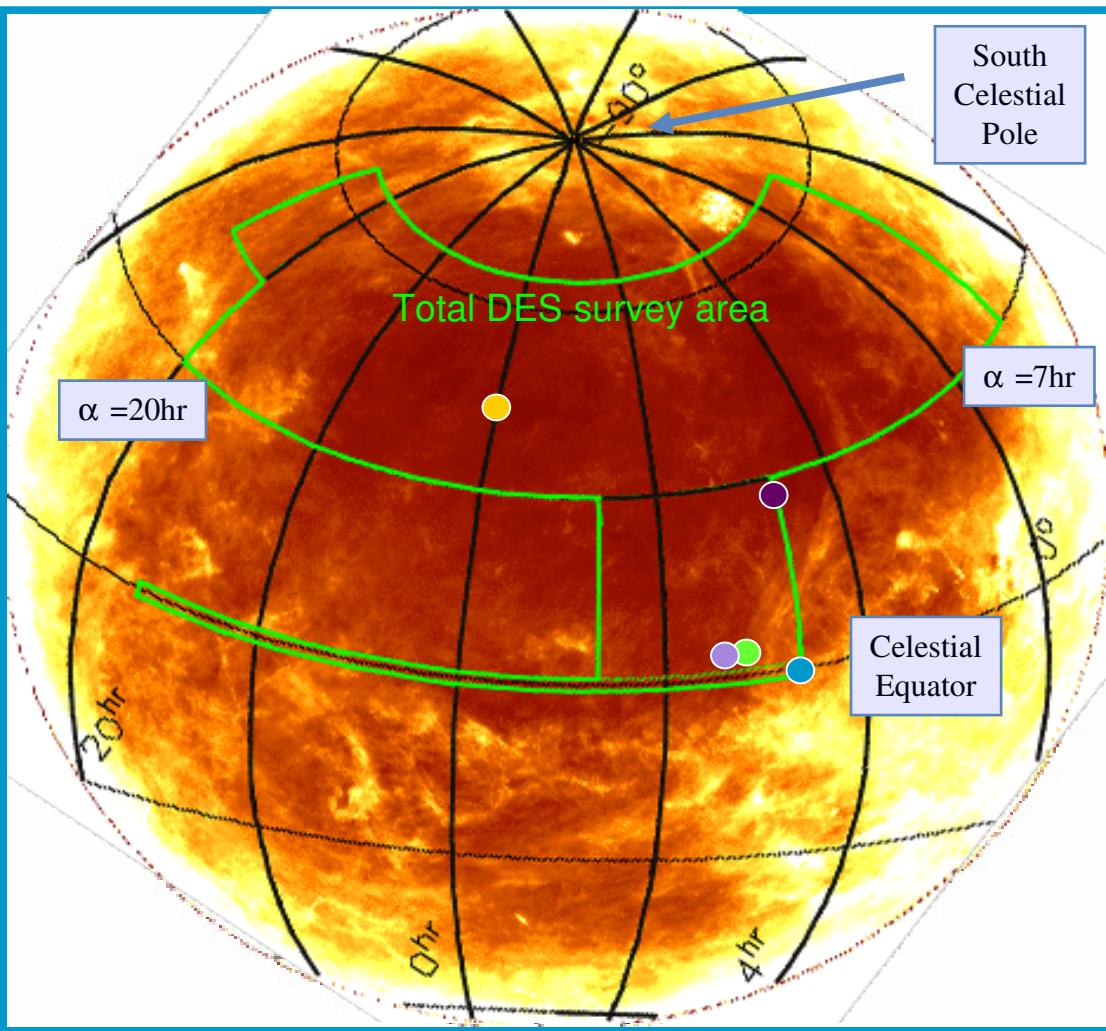
NB. distance $\propto \text{func}(z, \Omega)$

Current Favored DES Supernovae Fields

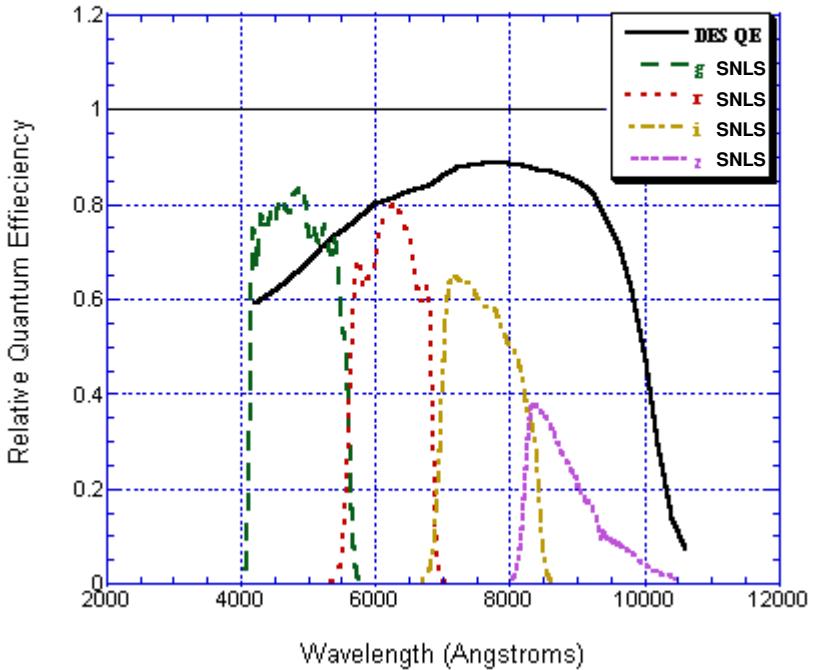
- Chosen to maximize:
 - visibility from DES site
 - past observation history
 - visibility from, e.g, Hawaii

Chandra Deep Field – South ●
 Sloan Stripe 82 ●
 SN Legacy Survey (SNLS) D1 ●
 XMM-Newton LSS ●
 ELIAS S1 ●

From a study by Peter Nugent



DES vs. Supernova Legacy Survey (SNLS)



DES uses thicker LBNL CCDs with increased red sensitivity ⇒ improved z-band performance

DES will also have 5–10 times better statistics

Courtesy: John Marriner

SNANA Software Package Used By DES

R. Kessler (U. Chicago), J. P. Bernstein, S. Kuhlmann, & H. Spinka (ANL)

- Software suite for simulating and fitting SN light curves
- Publicly available: http://www.hep.anl.gov/des/snana_package
- Allows an accurate & complete study of DES Supernovae observations including detailed filter characteristics, realistic weather & cadence considerations, dust extinction effects, CCD properties, etc.
- Also used by other projects
 - Sloan Digital Sky Survey (SDSS)
 - Large Synoptic Survey Telescope (LSST) SN project

SNANA SN Light Curve Fitter & Simulator

- Computes rest-frame model magnitudes using various models
- Applies random color/luminosity fluctuations
- Includes host galaxy dust extinction
- Applies K-corrections: transforms observed measurements at redshift z , into a standard measurement at redshift zero
- Sets choice of cosmology
- Applies Milky Way dust extinction via Schlegel maps*
- Converts magnitudes to flux
- Adds CCD gain, signal noise, and sky noise

Fitter included for resulting light curves

*Schlegel, Finkbeiner, Davis 1998, ApJ, 500, 525

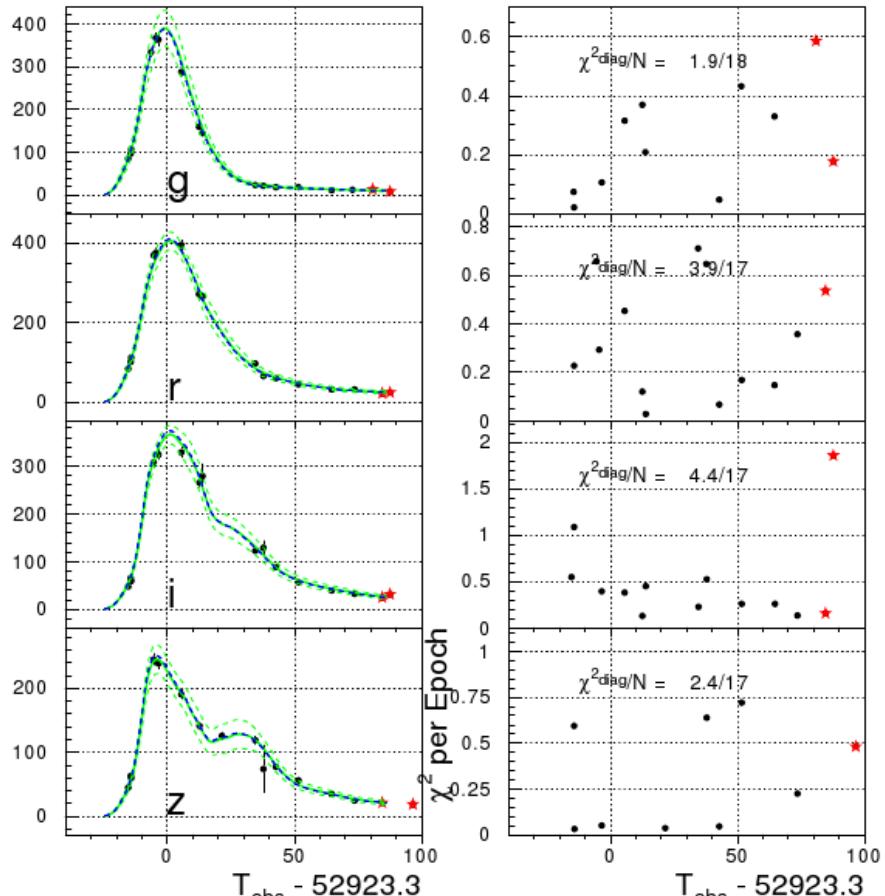
Multicolor Light Curve Shape Model

(MLCS2k2; Jha, Riess, Kirshner 2007, ApJ, 659, 122)

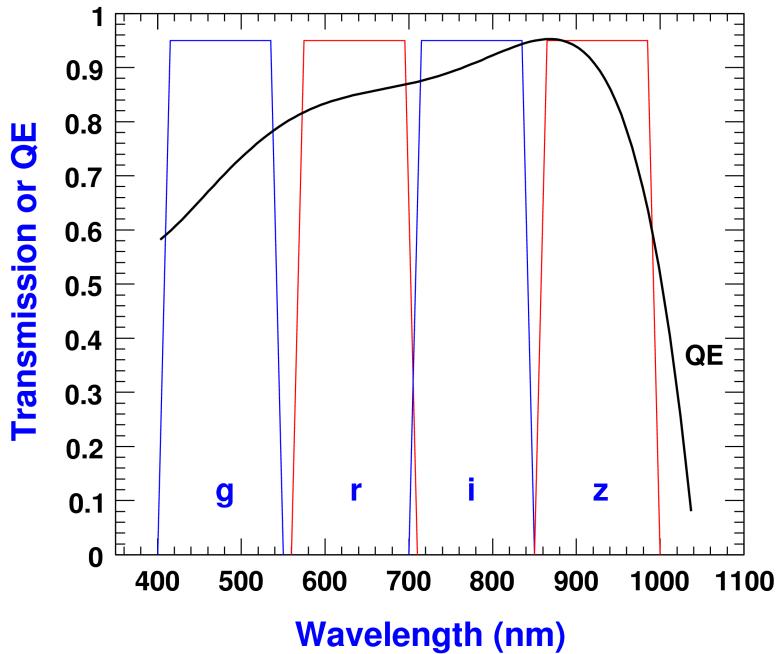
- Light curve model of apparent brightness as function of time
 - templates from observations give shape/brightness relation
 - accounts for dust extinction in Milky Way
- Free parameters
 - epoch of maximum light in B-band
 - distance modulus (μ)
 - luminosity/light curve shape parameter (Δ)
 - amount of extinction in magnitudes* (A_V) by host-galaxy dust

* Cardelli, Clayton, Mathis 1989, ApJ, 345, 245, and references therein

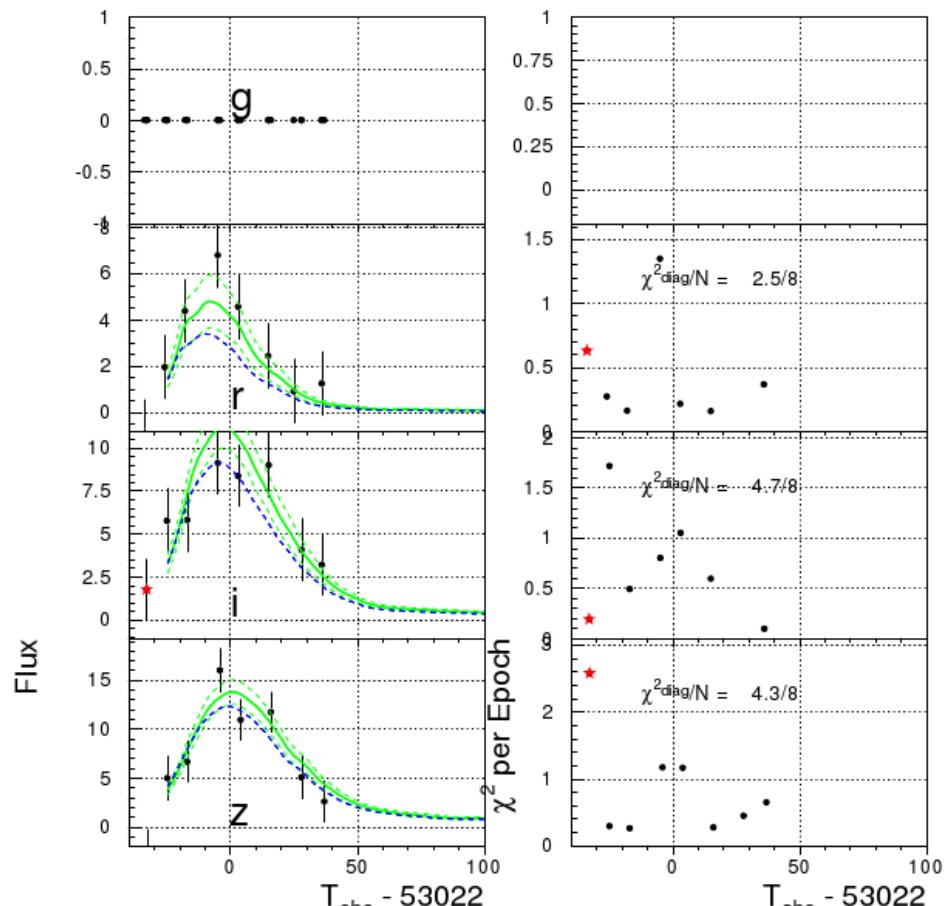
Simulated DES SN Light Curves



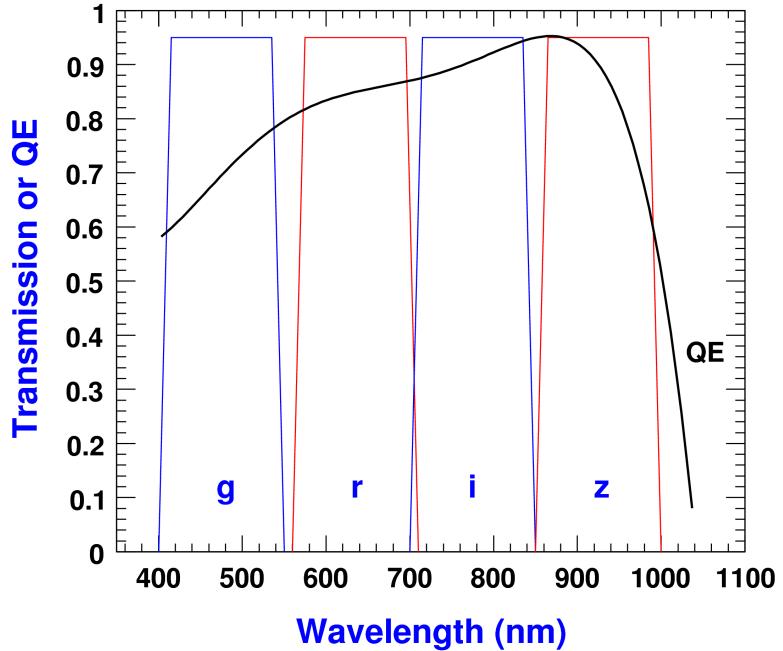
Example light curve at redshift of ~0.24 for a hybrid survey (15 sq. deg.) using the griz filter set – note 2nd bump unique to SNe type Ia



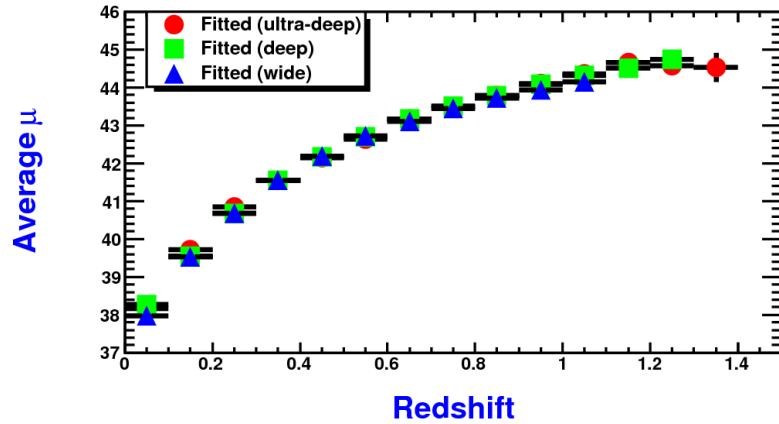
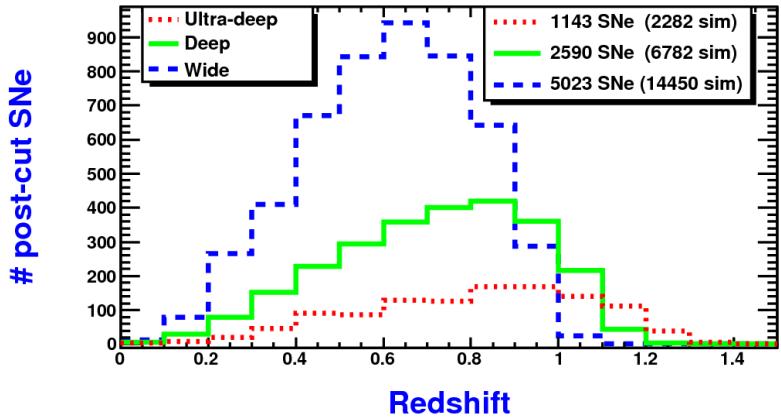
Simulated DES SN Light Curves



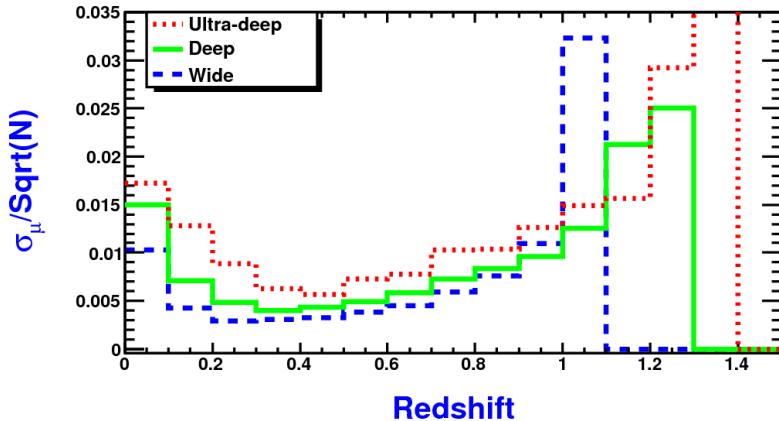
Example light curve at redshift of ~ 1.09 for a hybrid survey (15 sq. deg.) using the griz filter set – note lack of 2nd bump unique to SNe type Ia, and that g-band is redshifted out of range



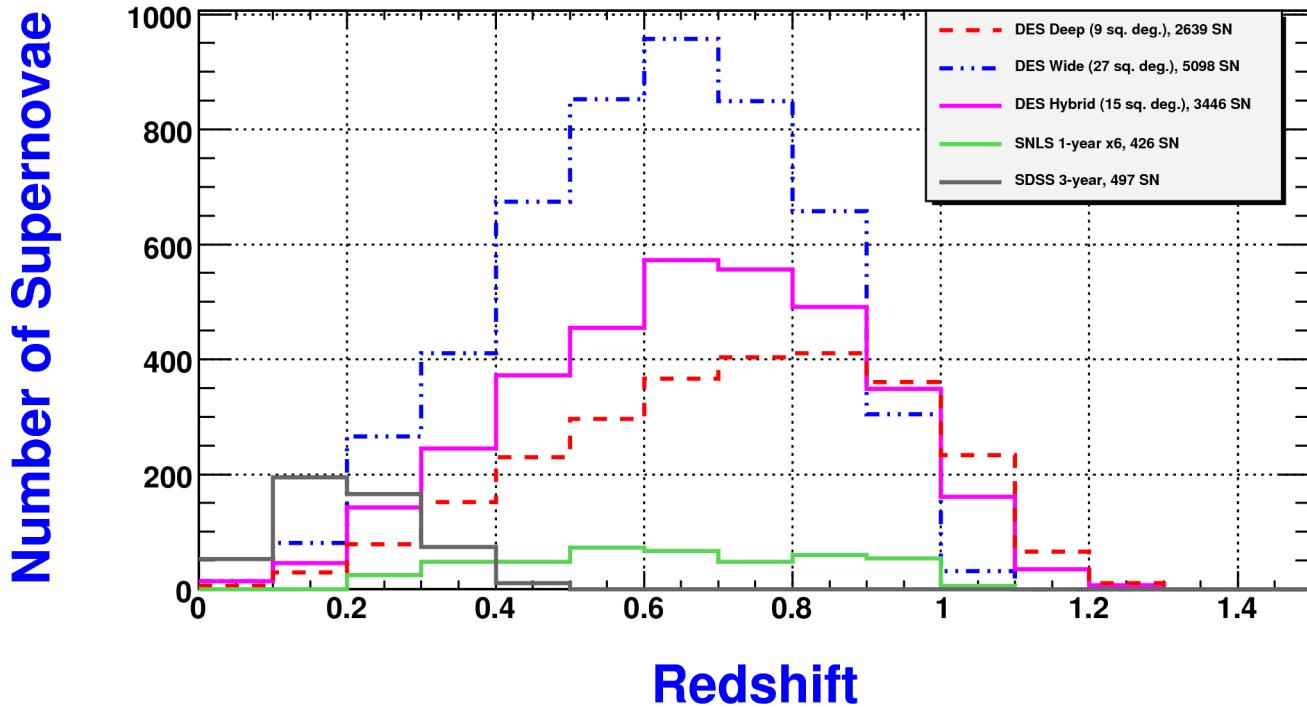
Number Of SNe & Statistical Distance Error



Error on the Hubble diagram for ultra-deep, deep, & wide surveys
 (3, 9, 27 sq. deg., respectively)



Comparison To Current Surveys



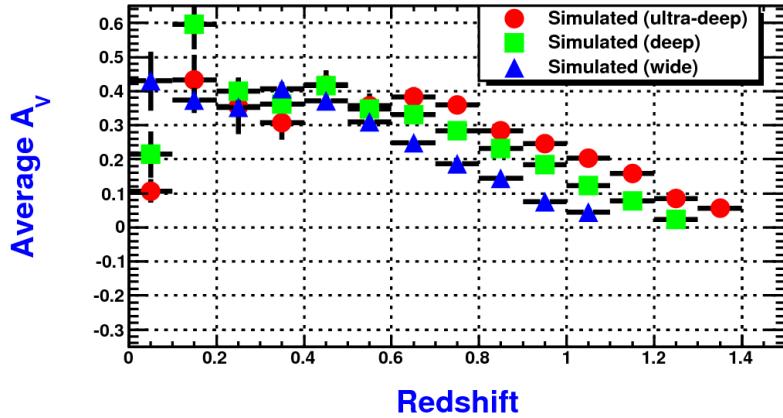
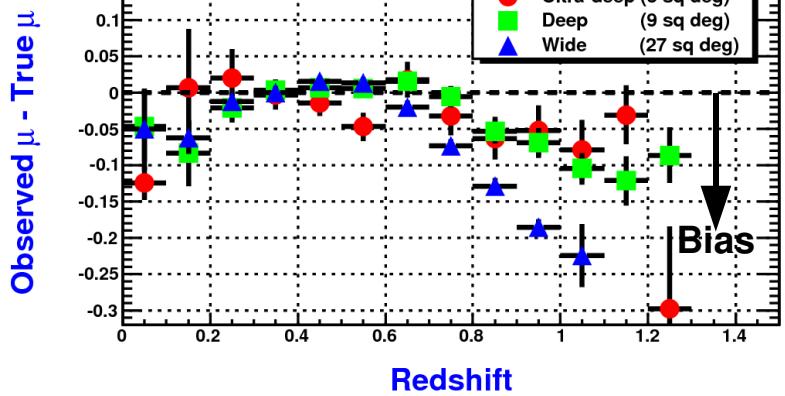
DES Systematics

- Systematics errors becoming dominant factor for SN cosmology
- Systematic effects to consider:
 - light curve model
 - dust extinction vs. intrinsic color
 - photometric calibration
 - non-1a background
- DES SN survey strategy: best FoM + control of above systematics
- DES SN working group shifting focus to systematics study

Summary & Conclusions

- Observations show Universe is composed of 95% weird stuff
 - ~21% dark matter
 - ~74% dark energy
- Dark energy: explanation of dimness of distant supernovae
 - fundamental physics mystery: what is it?
 - default theory: Einstein's cosmological constant
- Supernovae are excellent cosmological tools
- Dark Energy Survey (DES): next step in addressing dark energy
- DES simulates SN light curves via realistic SNANA package
- Light curves harnessed to optimize DES SN strategy
- Ultimately: peer reviewed DES SN strategy paper
- DES on schedule for first light in 2011

Sensitivity Of μ To Selection Efficiency



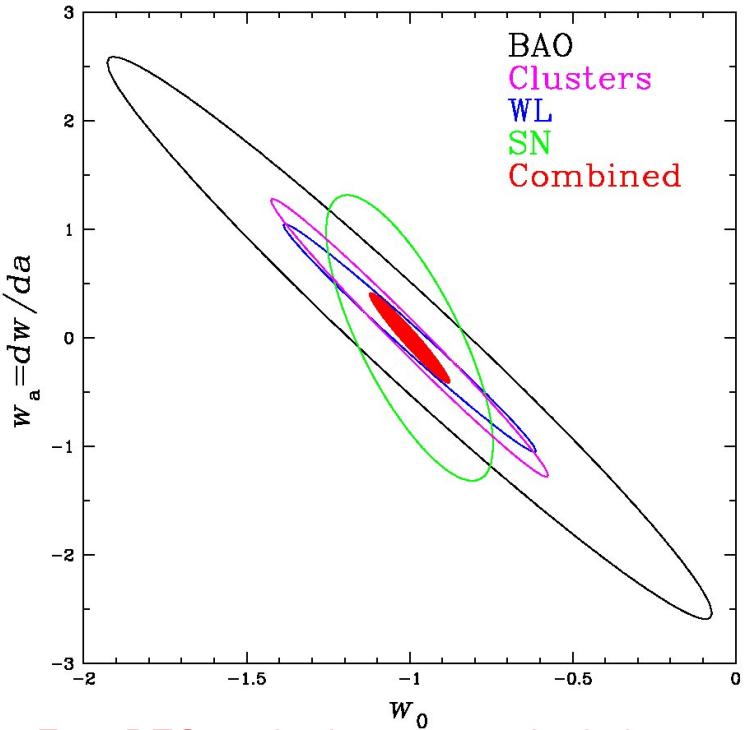
A bias in μ is evident in the difference in the fitted and simulated values, arises from selection efficiencies not being taken into account, and illustrates the magnitude of the μ -correction that will be needed

Survey Figure Of Merit (FoM)

- Dark Energy Task Force (DETF) FoM: inverse size of $w_a - w_0$ error ellipse

- $w(a) = w_0 + (1-a)w_a$
- a = scale factor
- $w_0 = w$ at present epoch
- $w_a = \text{rate of change of } w \text{ with } a$

- Inverse area means bigger is better



Four DES methods to constrain dark energy
 (plot from NSF/DOE proposal including Planck priors but NOT the DETF Stage II constraints)

Dark Energy Task Force (DETF) FoM For DES

